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Finite element investigation of the structural behaviour of deck slabs in composite bridges

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ABSTRACT

This research studies the structural behaviour of bridge deck slabs under static patch loads in steel–concrete composite bridges and investigates compressive membrane action (CMA) in concrete bridge decks slabs, which governs the structural behaviour. A non-linear 3D finite element analysis models was developed using ABAQUS 6.5 software packages. Experimental data from one-span composite bridge structures are used to validate and calibrate the proposed FEM models. A series of parametric studies is conducted. The analysis results are discussed and conclusions on the behaviour of the bridge decks are presented.

1. Introduction

In the past 40 years, it has become increasingly evident that durability of the concrete bridge deck slabs was directly related to the corrosion of reinforcement. De-icing salt has been one of the major factors in the deterioration of reinforced concrete bridge decks [2]. However, bridge deck slabs in the typical beam-and-slab type bridge have inherent strength due to in-plane forces set-up as a result of the restraint provided by the slab panel boundary conditions. This is known as compressive membrane action (CMA) or arching action [3,4].

Although the effect of compressive membrane action in concrete bridge deck slabs has been recognised for some time, it is only recently that there has been acceptance of a rational treatment of compressive membrane action in concrete slabs. Some design and assessment codes now acknowledge the benefits of CMA. These include the Department of Regional Development (NI), Design Specification for Bridge Decks [5]; The Canadian Highway Bridge Design Code [6] and the UK Highways Agency Standard BD81/02 [7]; the latter came about as a direct result of research at Queen's University Belfast [8–11].

In the past, most of research works on the structural behaviour of deck slabs under compressive membrane action has focused on experimental studies [8–12]. However, due to the high cost and significant time requirement in conducting full-scale physical testing, it is difficult to develop comprehensive parametric studies for this structural type. Furthermore, some structural values were difficult to measure by experimental tests, such as the stress–strain relationship through the depth of decks. Therefore, refined and completed studies are needed to investigate the structural behaviour of slabs on composite steel–concrete bridges, which are one of the most common types of bridge form. The availability of high-speed computers and commercial finite element packages facilitate the development of these tools through 3D FEA [13].

The objective of this paper is to study how the deck slabs work in composite bridges under the static patch loads and the remaining structural components of bridges influence the response of concrete deck slabs. To this end, a commercial software named ABAQUS [14], which accommodates non-linear 3D FEM models, can be employed. The proposed numerical model showed good convergence ability and an excellent agreement of structural behaviour with the validations of experimental tests by authors [12,15]. Subsequently, the observed structural behaviour of bridge deck slabs were presented. Finally, a series of parametric studies is conducted: (a) steel supporting beams; (b) presence and position of steel reinforcement; (c) presence of diaphragm; (d) connection between concrete slabs and steel beams.

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Table 1
Nominal variables in physical model.

Model no.	Concrete compressive strength* (N/mm^2)	Reinforcement percentage (%)	Main transverse steel		Main longitudinal steel		Support beam size (kg)
			Diameter (mm)	Spacing (mm)	Diameter (mm)	Spacing (mm)	
M36SB05	35.8	0.5C	8	200	8	200	305 × 102 × 25
M77SB05	77.0	0.5C	8	200	8	200	305 × 102 × 25
M38BB05	37.7	0.5C	8	200	8	200	305 × 165 × 54
M69BB05	68.8	0.5C	8	200	8	200	305 × 165 × 54
M33SB10	32.8	1.0C	10	150	6	200	305 × 102 × 25
M34BB10	33.8	1.0C	10	150	6	200	305 × 165 × 54

* The concrete strength was based on the cube test.

Nomenclature

f_c	Compressive stress
$f_{c'}$	Maximum stress
ε_c	Compressive strain
$\varepsilon_{c'}$	Strain when f_c reaches $f_{c'}$
n	Curve fitting factor, as n becomes higher the rising curve becomes more linear
Ec	Elastic modulus of concrete material
$\sigma_{1,2,3}$	Principle stress
α	Coefficient determined from the initial equibiaxial and uniaxial compressive yield stress
β	Function of plastic strain
I_1	First invariant of stress tensor [1]
J_2	Second invariant of stress deviator tensor [1]
$\langle\sigma_{\max}\rangle$	Algebraically maximum principle stress
$\gamma = 3$	For typical concrete, only appears in triaxial compression
f_{b0}	Biaxial compressive yield stress
f_{c0}	Uniaxial compressive yield stress
f_{t0}	Uniaxial tensile yield stress
f_y	Yield stress of steel reinforcement
f_{cu}	Compressive strength of concrete
σ_{bc}^u	Ultimate biaxial compression
σ_c^u	Ultimate uniaxial compression

2. Numerical model development, calibration and validation

2.1. Physical model

A series of one-third scaled steel–concrete composite bridge model tests were conducted by authors [15] at Queen's University of Belfast. The test models were designed to represent an external bay of a typical composite steel–concrete bridge at one-third scale. The continuity of slabs in the central bays of a typical bridge structure provides restraint and therefore enhances the compressive membrane action. A summary of the experimental details is presented in Table 1 and Fig. 1. As shown in Table 1, the name of the model includes all of its structural variables. For example, for Model M36SB05, 36 is the concrete compressive strength, SB means the supporting beam is small, and 05 is the reinforcement percentage (0.5%).

2.2. NLFEA bridge model

In 3D numerical modeling, the bridge deck can be built using shell or solid elements. The steel supporting beams can be simulated as shell, solid or beam elements [16]. In order to establish the best combination of elements to found out the one that performs best, three models were built and compared to find the best models. In this study, the shell element (S8R or S4R) was selected to model concrete bridge decks, steel supporting beams and diaphragms, as shown in Fig. 2. These elements considered transverse shear flexibility and membrane strains. Full composite action between the RC bridge deck slabs and steel supporting beams was assumed and developed using beam type multipoint constraints (MPC beam [14]) between the top flange of steel I beam and concrete slabs, which assures the nodal compatibility at those locations.

In order to improve the accuracy of the NLFEA, it has been found that consideration must be given to the mesh density selection. The research from Bažnat and Cedolin [17] showed that the element size should be optimised, where the smaller elements are capable of eliminating an unrealistic lower predicted strength due to the effects of stress concentrations, and the incorporation of relatively large elements reduces the need to modify the constitutive model to prevent an overestimation of the energy dissipation capacity. Therefore, the element size is selected to achieve a balance between two objectives. The basic finite element is shown as Fig. 2. The steel reinforcement was simulated as rebar layers embedded into the shell element of concrete bridge deck slabs.

2.3. Reinforcement concrete material and calibration

2.3.1. Constitutive models

Steel and reinforcement

This analysis incorporates full nonlinear material behaviour including a bilinear stress–strain response for structural steel material model, including the steel for supporting beams and steel reinforcement. Classical metal plasticity models are used for the nonlinear material effects of both steel beam and reinforcement. Specifically, the Von Mises yield criterion with associated plastic flow and isotropic hardening are used.

Concrete

Fig. 3 shows the model for uniaxial compressive behaviour of concrete materials provided by Thorenfeldt et al. [18] with the Hognestad's [19] assumption on the elastic modulus of concrete. The relationship of stress–strain in this theoretical model was shown in Eq. (1).

$$\frac{f_c}{f_{c'}} = \frac{\varepsilon_c}{\varepsilon_{c'}} \frac{n}{n - 1 + (\varepsilon_c/\varepsilon_{c'})^{nk}} \quad (1)$$

$$\varepsilon_{c''} = \frac{f_{c'}}{E_c} \frac{n}{n-1} \quad (2)$$

$$n = 0.8 + \frac{f_{c'}}{17} \quad (3)$$

when $\varepsilon_c/\varepsilon_{c'}$ is less than 1, k equals 1,

when $\varepsilon_c/\varepsilon_{c'}$ is exceeds 1, k is number larger than 1

$$k = 0.67 + \frac{f_{c'}}{62} \quad (4)$$

$$E_c = 4723\sqrt{f_c'}. \quad (5)$$